Aspects of Network Harmonic Impedance Modelling in High Voltage Distribution Networks

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***Abstract*— This paper evaluates the performance of five leading power system analysis softwares in terms of network harmonic impedance calculation for High Voltage distribution grids. Based on a set of systematic case studies the first part of the work presents a comparative analysis of the software packages in calculation of first resonance point. The different network element models and load models and their impact on the resonance parameters are discussed in detail. The second part of the research work assesses the sensitivity of the resonance parameters (impedance magnitude and frequency) depending on the change of certain network model parameters and compares the results amongst the different software packages. This gives an idea about the robustness of frequency and magnitude response at the resonance point and points out the most sensitive parameter in a HV network.**

***Index Terms*—Frequency Sweep, Harmonic impedance, High Voltage (HV) distribution network, Resonance.**

I. Introduction

The measurement of harmonic impedance in a power system network has gradually gained importance with the installation of power electronics based equipment which injects harmonics into the network (e.g. large converter stations). For typical European Low voltage (LV) and Medium voltage (MV) distribution networks the first resonance frequency is usually above 1kHz (20^{th} order). So resonance problems are usually not an issue. On the other hand in High voltage (HV) distribution networks resonances can occur at frequencies well below 1kHz thus making it a matter of serious concern. For LV and MV networks in calculations (e.g. of emission limits) often resonance are neglected and the simplified impedance line is used. While this simplification is adequate for LV networks and partly for MV networks too, its application to HV networks can lead to unallowable high inaccuracies at the important harmonic orders, like 5^{th} or 7^{th}.

In most cases emission limits for lower order harmonics of equipment or installations are based on currents. Following the basic EMC concept the value of voltage harmonics in the grid has to meet compatibility levels or planning levels respectively to ensure satisfactory operation of all other equipment connected to this grid. The accurate calculation of current emission limits based on permissible voltage harmonic levels needs reliable information about the harmonic impedance.

One way to assess the network harmonic impedance is measurement. Over the years many harmonic impedance measurement methods have been proposed by researchers worldwide. Most of these methods are applicable for MV and LV networks [1-6]. Only a few publications are available on measurements of the harmonic impedance in HV networks [7, 8]. This is due to the fact that reliable measurement of harmonic impedance at HV level needs usually complex, cost-intensive setups and often involves a significant intervention to the network operation, which is certainly not accepted by the network operator.

Another possibility to obtain the harmonic impedance is the simulation of the HV network in a harmonic analysis software package. In an earlier project harmonic impedance of a particular 110-kV-grid was simulated by using two different software packages (one from the network operator, one at the university). The network schema was similar in both software, but the obtained results differed significantly. To identify the reasons for the differences and to verify the performance of other software packages, a comparison of 5 different packages based on a reference grid with a distinctive resonance was carried out and the results are presented in this paper. Particular focus was set on the study of various models of the different network components present in each of the software and the possible impact of model parameter variation on the harmonic impedance.

This paper is organized as follows: the developed reference network is introduced in section 2. Section 3 gives an overview of selected software packages and a brief discussion on the different network component models included in them. The implementation of the reference network in each software package and the comparative analysis by different case studies are presented in section 4.

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Section 5 deals with the sensitivity analysis of the first parallel resonance (frequency and impedance magnitude).

II. Reference Network

The typical behaviour of a European HV distribution network should be exhibited by a reference network. Therefore, instead of using one of the IEEE test networks, a reference network based on the typical parameters of a meshed HV distribution network was developed having distinct resonances well below 1 kHz.

The network consists of 14 buses with 3 infeed points. Infeed 1 is maintained as reference bus at a nominal voltage level of 220 KV (line to line voltage). The total rating of the infeed transformers is 600 MVA. To meet the (n-1) criteria the cumulative load under full load condition shall be kept a little below 70% of the total infeed transformer rating. So, the total connected load is 400 MW at 0.98_{ind} power factor. This is realized by connecting 22 equivalent downstream loads having two types of load modelling, a series R and L model and Cigre type C load model. The details of these models are discussed in the next section. All the equivalent loads are connected to the HV network by 40 MVA transformers and each of these combinations is formed as a subsystem and represented as square box in the network diagram shown in Fig.1

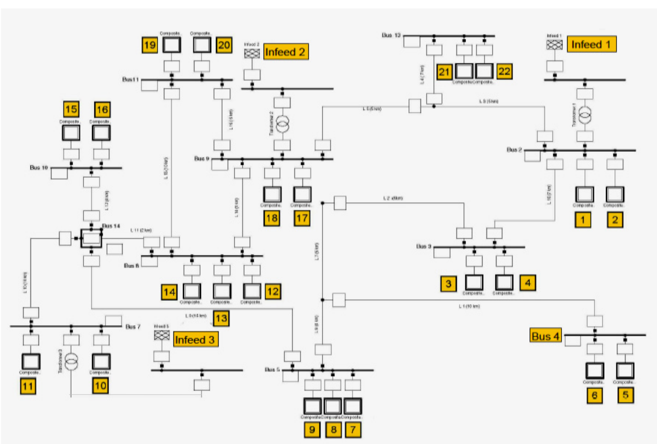

Figure 1. 110 KV Reference Network

The short circuit power at each of the 110-kV-buses is limited to 4 GVA, which is a realistic value for the considered grid. Based on the length and the type of the lines two different scenarios are distinguished. A cable network with average line length of 10 km represents a typical HV distribution grid in urban regions while an overhead line network with average line length of 25 km represents typical rural regions.

III. Software Packages And Component Models

A. *Software overview*

A lot of different software packages for power system analysis are available in the market. Most of them offer the possibility of harmonic simulation. Fig.2 gives an overview of the selected simulation packages with integrated harmonic analysis module. However due to different types of component models some of them are more suitable for harmonic analysis than others.

SOFTWARES	TRANSMISSION LINE MODEL	TRANSFORMER MODEL	LOAD MODEL
1	Distributed	Classical	Series connected inductive/capacitive
	Lumped	High frequency	Mixed inductive/capacitive
2	Distributed (with frequency dependency of R and L)	Classical	Series RL
	Lumped	High frequency	Parallel RL
3	Distributed (based on Bergeron's model)	Classical	Series RL
	Lumped		Parallel RL
4	Distributed	π Equivalent circuit	Series RL
	Lumped		Parallel RL
5	Equivalent π model	π Equivalent circuit	Passive Parallel load model

Figure 2. Different component models in the selected software

Some software packages having frequency dependent transmission line model requires detailed information on tower and conductor geometry. Due to time constraint and unavailability of accurate data these packages are excluded from the comparison.

B. *Component models*

1) *Transmission line model*

From Fig.2 it can be seen that almost all software packages have a *lumped* and a *distributed* model. The lumped model represents the nominal π model which is used for short transmission lines. With the increase in line length or frequency, distributed parameter model becomes important.

The distributed model provided by software 2 partly differs from the other softwares because of the inherent frequency dependency of transmission line resistance and inductance. This model is selected by default for harmonic analysis without the option to change it to the lumped model for comparative analysis. Software 3 provides a distributed model based on Bergeron's model for EMTP analysis, which means it neglects the transmission line losses. Software 5 only uses a π equivalent model, where the number of π-elements is automatically determined by the line length. Strictly speaking this is not a true replacement for distributed parameter model and thus it may lead to inaccuracies when the line length and operating frequency increases.

2) *Transformer model*

Mainly two types of model are present in the softwares, the *Classical model* and the *High frequency model*. The later includes the inter-winding capacitances and the bushing capacitances thus making it more suitable for transient analysis. Hence the classical model is used for all the case studies. Software 4 and software 5 mention explicitly, that the classical model is implemented as a π equivalent circuit having two nodes, instead of the more common T equivalent circuit having three nodes. But this should not influence the simulation results at all.

3) *Load model*

Two types of load modelling have been implemented in the reference network, the *default load model* and the *Cigre* *type C load model.* The default load model is a series connection of resistance (R) and inductance (L). Software 1 selects this model by default while performing harmonic analysis. Other software packages allow the selection of either a series RL connection or a parallel RL connection. For comparing the software on the same ground the series RL connection is always used for the first type of load model.

The Cigre model was designed by the Cigre working committee and is especially designed for MV-load modelling for harmonic impedance analysis [9]. Over a frequency range corresponding to harmonics between 5th and 20th order the loads are represented by the scheme as shown in Fig.3.

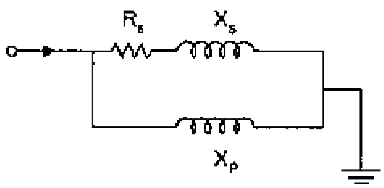

Figure 3. Cigre Type C load model (source: [10])

The element parameters are calculated as follows:

$$R_s = \frac{V^2}{P} \quad (1)$$

$$X_s = 0.073 \times h \times R_s \quad (2)$$

$$X_p = \frac{h \times R_s}{6.7\frac{Q}{P} - 0.74} \quad (3)$$

The parameters are nominal voltage V and active and reactive powers P and Q at 50Hz.

IV. Comparative Analysis

The reference network introduced in Fig.1 has been implemented in each of the above mentioned softwares. To ensure exact representation of the network, load flow results had to be similar between the different software packages before proceeding with further case studies.

A. Overview of possible case studies

Based on the different parameters present in the reference network, like load model, transmission line type and the different loading states, a set of possible cases was formulated. The different variable parameters including the possible values are listed in the following Fig. 4.

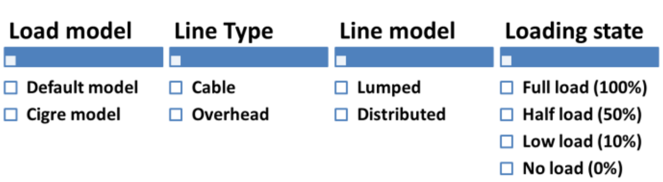

Figure 4. Overview of variable network parameters and their values

Based on the table in Fig.4 a total of 128 case studies have been carried out in the first 4 software packages. The results of the first case in software 5 are significantly different with the other software packages and hence no further cases have been carried out in it. All simulations consider only positive sequence system. The specific behaviour of zero sequence impedance wasn't considered in this stage.

Fig.5 shows a typical frequency sweep analysis plot with the worst performing bus marked with an arrow at the first parallel resonance point. The worst performing bus is the one from which maximum harmonic impedance of the network is perceived. For the reference network this is always bus 4.

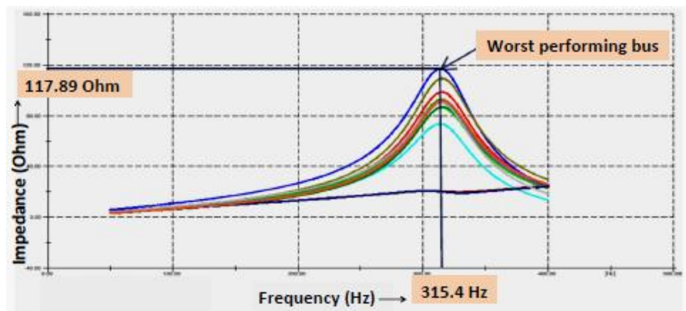

Figure 5. Network harmonic impedance from different buses

B. Scenario I: Default load model, distributed line model, cable network

All the 22 downstream loads are modelled as series connection of R and L. The total network is considered to have only cable transmission line. Keeping these parameters constant, the loading state is now varied from a full load condition, which is equal to 70% of the total rating of infeed transformers, to half load and low load condition respectively. The results obtained from the five softwares for the first resonance point at the worst performing bus are given in Fig.6.

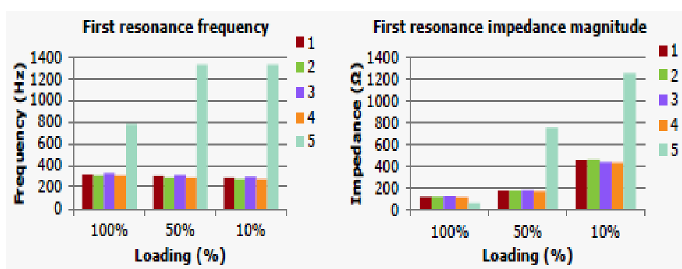

Figure 6. Results for scenario I

Fig.6 shows that both the frequency and magnitude response lies well within 5% range for the software 1 to 4. Just for illustration the significant different results of software 5 are shown too.

C. Scenario II: Cigre load model, distributed line model, cable network

Keeping the transmission network same as in the previous scenario, all the downstream loads are now replaced by Cigre Type C load model. Fig.7 shows the results, but for software packages 1 to 4 only.

The comparison of the results in Fig.6 and Fig.7 points out two important conclusions. While frequency of first resonance point is similar for both scenarios, the Cigre load model provides a much more realistic damping behaviour than the simple series RL model. Magnitude and quality factor for Cigre load model are smaller than for the series RL model. This proves that Cigre model is the more realistic model for harmonic impedance analysis.

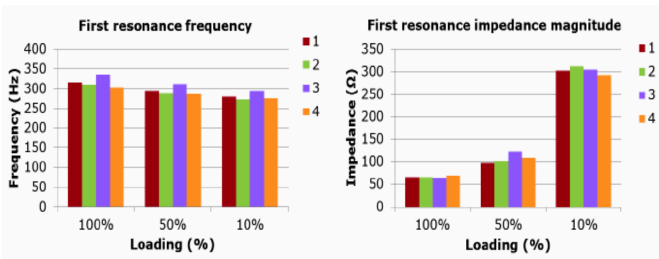

Figure 7. Results for Scenario II

D. *Comparison of lumped and distributed line model for Scenario II*

The distributed line model is recommended for line lengths much longer than the ones in the reference model. However due to the analysis of frequencies significantly higher than power frequency it may be necessary to switch from lumped to distributed model even for small line lengths. The results of the comparison are shown in Fig. 8.

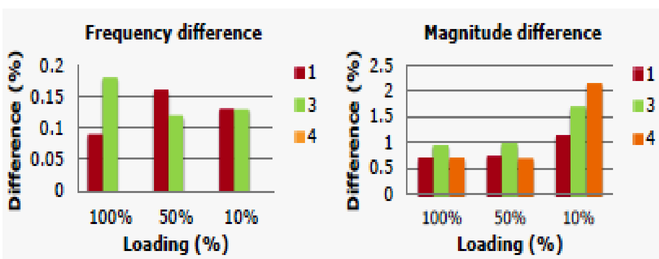

Figure 8. Percentage difference between lumped and distributed parameter

Results from software 2 are absent as it does not support lumped parameter model for harmonic analysis. The results from other softwares show insignificant difference between the two types of line modelling. No bar is visible for the frequency difference of software 4, because the software delivers same results for both the line models.

E. *Summary*

Load modelling has a significant impact on overall damping of the network and thus significant influence on the quality factor. So it is extremely important to model the downstream equivalent load as accurately and appropriately as possible. However if only resonance frequency is considered, then load modelling does not have a significant impact.

The maximum of the first parallel resonance is much smaller and the bandwidth is much wider in case of a cable network. In terms of quality factor an overhead line network will always have higher quality factor compared to a cable network Moreover a cable network has always a lower resonance frequency as an overhead line network of comparable size.

For distribution networks of small size the results are almost independent from the chosen transmission line model (lumped or distributed) unless the considered frequencies exceed 2 kHz.

V. SENSITVITY ANALYSIS

As it has been discussed before, one of the most practical solutions for harmonic impedance assessment is simulation. Though it may seem to be a lot easier than doing a measurement, in reality there are certain points which makes it difficult to perform accurate simulations. Examples are availability of accurate data for all the required model parameters or incorporation of time-dependent parameter variations, which is typical for real networks.

To address these issues, a sensitivity analysis is performed to assess the influence level of a particular parameter to the overall harmonic impedance of the network. This gives a first idea of the maximum permissible error which is allowed in the input data of certain parameters without affecting the results too much.

A. *Overview of possible case studies*

The parameters of the following network components are varied for the sensitivity analysis: infeed transformers, load transformers, transmission lines. Each of the transformers has a series component which includes the leakage reactance and the winding resistance and a shunt component which includes the magnetizing reactance and core loss resistance. The transmission lines have a series resistance and reactance, and a shunt capacitance. The shunt conductance is neglected.

Based on these parameters a set of 66 practical case studies have been formed. The cases include different loading states as well as different type of network (cable, overhead line). For each of these cases the parameters are changed by ±10% with respect to the base value. Due to the similarity of the results of software 1 to 4, software 1 was chosen for the detailed sensitivity study.

The results show that the harmonic impedance is more sensitive to certain parameters than to others. Therefore all above mentioned parameters are classified in three categories based on their sensitiveness towards the first resonance frequency and impedance magnitude. From each category the parameter showing most consistent behaviour is shown in Table I.

TABLE I. CATEGORISATION OF NETWORK PARAMETERS

Most sensitive parameter	**Medium sensitive parameter**	**Least sensitive parameter**
Line capacitance	Infeed transformer series reactance (flux leakage component)	Infeed transformer shunt reactance (magnetizing component)

In the second step the parameters in Table 1 are used to verify, if the sensitivity in the different software packages are comparable. Results for one of the case studies (full load condition, cable network) are presented in Fig.9. The software packages 1 to 3 show almost identical behaviour, which could be observed for the other cases in a similar way. Software 4 behaves slightly different, but within an acceptable range.

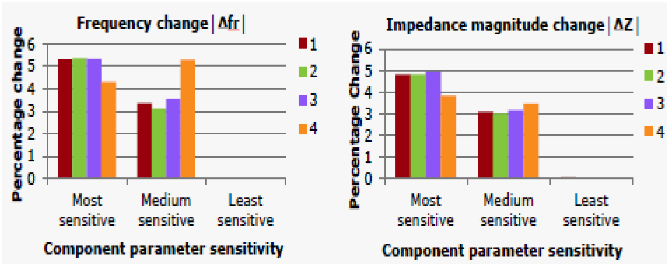

Figure 9. Network component sensitivity at the first resonance point

To study the linearity of the influence, the parameter with highest influence (line capacitance) on the harmonic impedance is varied in the range ±30% in steps of 10% in all software packages. The results for frequency and impedance magnitude at first parallel resonance are presented in Fig.10.

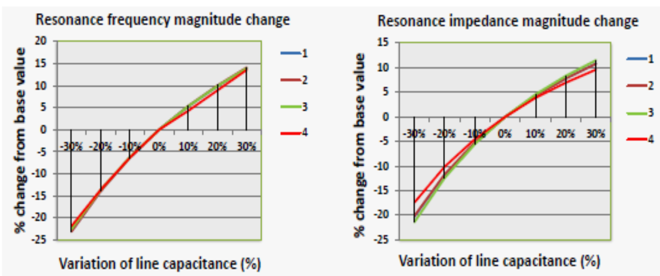

Figure 10. Variation of resonance parameters

Fig. 10 shows that all software packages have equal behaviour in terms of sensitivity. A non-linear relationship can be observed, which is slightly higher for the impedance magnitude change at resonance point.

B. Summary

In a cable network the impedance magnitude is more robust to the change of the parameters compared to the resonant frequency. This is observed for full load and low load states. However, under no load condition the frequency is found to be more robust compared to the impedance.

In an overhead line network a completely opposite behaviour is found. In this case the frequency shows a more robust response compared to the impedance magnitude for full load and low load states. However, under no load condition no such specific behaviour can be found.

VI. CONCLUSION

This paper presents a comparison of the performance of different power system analysis software packages in terms of calculating the network harmonic impedance. The study focuses on HV distribution networks, how they are typical for Central European countries. 4 out of 5 selected software packages show similar and consistent results. Hence simulation of harmonic impedance of HV distribution networks is in most cases easier than measurement, but care has to be taken for consistent and accurate input parameters. E.g. the type of load model has a significant influence on the calculated impedance magnitude. The impact of imprecise parameter values is studied by a sensitivity analysis. Line capacitance was found to have the highest impact on the accuracy of the calculated resonance. The sensitivity behaviour of the different software packages doesn't show any significant difference. The performance comparison shows that at least the first 4 analysed software packages are well suitable for harmonic studies. There is no explicit best-performing software.

This study has only shown the differences in the results between different software packages. To determine the absolute accuracy of the results, simulations have to be compared with real measurements. Implementing a real HV distribution network in software 1 and performing respective measurements of the harmonic impedance are planned in the near future. Moreover with the developed simulation environment the work on the harmonics part of the HV amendment to [10, 11] could be efficiently supported.

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